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PRINCIPLE OF THE CONSTRUCTION OF SELF-TUNING LOOPS
FOR SERVO SYSTEMS OF COMBINED CONTROL

by

B.V. Novoselov

FOREIGN TECHNOLOGY DIVISION

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Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

*ye initially, after vowels, and after ъ, ь; e elsewhere.
When written as ё in Russian, transliterate as yё or ё.

RUSSIAN AND ENGLISH TRIGONOMETRIC FUNCTIONS

Russian	English	Russian	English	Russian	English
sin	sin	sh	sinh	arc sh	$\sinh^{-1}$
cos	cos	ch	cosh	arc ch	$\cosh^{-1}$
tg	tan	th	tanh	arc th	$\tanh^{-1}$
ctg	cot	cth	coth	arc cth	$\coth^{-1}$
sec	sec	sch	sech	arc sch	sech^{-1}
cosec	csc	csch	csch	arc csch	csch^{-1}

Russian	English
rot	curl
lg	log

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PRINCIPLE OF THE CONSTRUCTION OF SELF-TUNING LOOPS FOR SERVO SYSTEMS OF COMBINED CONTROL.

B. V. Novoselov.

I. Formulation of the problem.

The use/application of servo systems of the combined control (SSKR) allows during the final adjustment of the specific type of input effects (VV) to theoretically ensure the complete compensation for the steady errors. However, the transiency of the parameters and the nonlinearity of the characteristics of elements/cells of SSKR cause the disturbance of the conditions for the compensation for the components of errors and, therefore, an increase in the error, frequently up to the inadmissible values.

Let SSKR be carried out on the diagram in Fig. 1a, where

$$K(p) = \frac{K}{p(1+T_1 p)(1+T_2 p)};\quad \varphi(p) = \varphi p - \varphi' p^2. \qquad (1)$$

Expressions of kinetic θ_{κ}, dynamic θ, of errors and condition for

their complete compensation

$$\Theta_x = \frac{1 - K\varphi}{K}\Omega_1; \; \varphi = \frac{1}{K}, \; \Theta_y = \frac{T_1 - T_2 - K\varphi'}{K}; \; \varphi' = \frac{T_1 - T_2}{K}. \qquad 1.2)$$

With the disturbance of condition $\varphi = \frac{1}{K}$ (change in the factor of amplification of SSKR K or change KS φ) $\Theta_\kappa \neq 0$ takes

$$\Theta_\kappa = \frac{1 - (K \mp \Delta K)\varphi}{K \mp \Delta K}\Omega_1 = \frac{\mp \frac{\Delta K}{K}}{1 \mp \frac{\Delta K}{K}}\Omega_{\kappa 0},$$

$$\Theta_\kappa = \frac{1 - K(\varphi \mp \Delta\varphi)}{K}\Omega_1 = \pm \Delta\varphi K \Theta_{\kappa 0}, \qquad 1.3)$$

where $\Theta_{\kappa 0} = \frac{\Omega_1}{K}$ value Θ_κ in the absence of KS.

From analysis (1.3) it follows that in the series/row of practical tasks it is necessary to introduce the automatic tuning of the parameters of SSKR as a function of the variable parameter. It is expedient to produce tuning of KS, since in this case there is no need for solving compromise problem during the guarantee of high accuracy and stability.

II. Theory of SSKR with KSN of KS.

Fig. 1b depicts the block diagram of SSKR, in which the parts of KS, developed by differentiators (Dif 1), (Dif 2), are multiplied in the blocks of product (BP1) (BP2) by the output signals of integrators (I1), (I2) actual error of SSKR by which is realized the

required change of KS with the disturbance of the conditions for error compensation.

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In this diagram is realized actually the integral control with the variable coefficients of integration, which are functions of VV. This control provides during the final adjustment of VV the elimination of the steady errors regardless of the fact the fact that was the reason for their appearance, and does not affect the quality of free transient processes.

Work of SSKR with KSN is described by nonlinear equation with the variable coefficients

$$
\begin{aligned}
& T_1 T_2 \frac{d^3\Theta}{dt^3} + (T_1 + T_2)\frac{d^2\Theta}{dt^2} + \frac{d\Theta}{dt} + K\Theta + \\
& + K[\varphi_0 + \varphi_0(t)]\frac{d\Theta_1}{dt}\int_0^t W_1(\Theta)dt + K[\varphi_0' + \varphi_0'(t)]\frac{d^2\Theta_1}{dt^2}\int_0^t W_1(\Theta)dt = \\
& = T_1 T_2 \frac{d^3\Theta_1}{dt^3} + (T_1 + T_2)\frac{d^2\Theta_1}{dt^2} - K[\varphi' - \varphi'(t)]\frac{d^2\Theta_1}{dt^2} - \\
& - K[\varphi + \varphi(t)]\frac{d\Theta_1}{dt}. \qquad (2.1)
\end{aligned}
$$

Let us assume that $\varphi_0(t)$, $\varphi_0'(t)$, $\varphi(t)$, $\varphi'(t)$ - the slowly changing functions, i.e., a change in them is unessential for the time of the effective duration of transient response of SSKR. Then the formulation of the problem will be the following. At the moment of time t=0 are disrupted the conditions for compensation Θ_1, Θ.

$$\varphi_{\kappa} = \varphi - \varphi(t) = \frac{1}{K},$$

$$\varphi_{\kappa}' = \varphi' - \varphi'(t) = \frac{T_1 - T_2}{K}.$$

Self-tuning loops must ensure the elimination of the steady errors.

We introduce designations

$$a_1(t) = W_1 \frac{d\omega}{dt}; \; a_2(t) = W_1' \frac{d^2\omega}{dt^2} \quad (2.$$

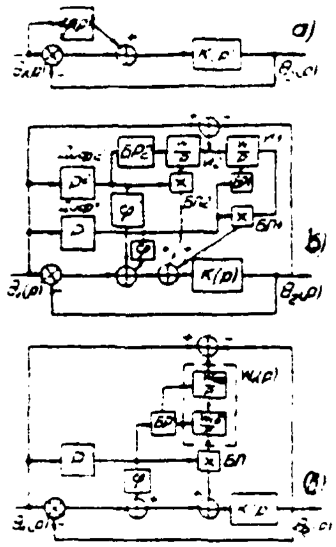

Fig. 1. Block diagrams of SSKR.

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After dividing left and right side of (2.1) by $\alpha_1(t)+\alpha_2(t)$ (sum $\alpha_1(t)+\alpha_2(t)\neq 0$ except when t=0) and differentiating with respect to t, we will obtain

$$a_0(t)\frac{d^4\Theta}{dt^4}+\left[\frac{da_0(t)}{dt}+a_1(t)\right]\frac{d^3\Theta}{dt^3}+\left[\frac{da_1(t)}{dt}+a_2(t)\right]\frac{d^2\Theta}{dt^2}+$$
$$+\left[\frac{da_2(t)}{dt}+a_3(t)\right]\frac{d\Theta}{dt}+\left[K+\frac{da_3(t)}{dt}\right]\Theta=$$
$$=b_0(t)\frac{d^4\Theta_1}{dt^4}+\left[\frac{db_0(t)}{dt}+b_1(t)\right]\frac{d^3\Theta_1}{dt^3}+$$
$$+\left[\frac{db_1(t)}{dt}+b_2(t)\right]\frac{d^2\Theta_1}{dt^2}+\frac{db_2(t)}{dt}\frac{d\Theta_1}{dt},$$

where

$$a_0(t) = \frac{T_1 T_2}{\alpha_1(t)+\alpha_2(t)};\quad a_1(t) = \frac{T_1+T_2}{\alpha_1(t)+\alpha_2(t)};\quad a_2(t) = \frac{1}{\alpha_1(t)+\alpha_2(t)};$$

$$a_3(t) = \frac{K}{\alpha_1(t)+\alpha_2(t)};\quad b_0(t) = \frac{T_1 T_2}{\alpha_1(t)+\alpha_2(t)};$$

$$b_1(t) = \frac{T_1+T_2-K\varphi_\kappa'}{\alpha_1(t)+\alpha_2(t)};\quad b_2(t) = \frac{1-K\varphi_\kappa}{\alpha_1(t)+\alpha_2(t)}.$$

Equation (2.3) - equation with variable coefficients. General solution it to obtain complicatedly. But according to the form of equation itself (2.3) it is easy to establish/install the conditions for the compensation for separate components of error.

When $\Theta_1(t) = \Omega_1 t$ $\Theta_\kappa = 0$, if

$$\frac{db_2(t)}{dt} = \frac{d}{dt}\left[\frac{1-K\varphi_\kappa}{W_1\frac{d\Theta_1}{dt} + W_1'\frac{d^2\Theta_1}{dt^2}}\right] = 0. \qquad (2.4)$$

When $\Theta_1(t) = \frac{\varepsilon_1 t^2}{2}$ $\Theta_\kappa = 0$, if

$$\frac{db_1(t)}{dt} - b_2(t) = 0,\quad \frac{db_2(t)}{dt} = 0. \qquad (2.5)$$

In the case $\Theta_1(t) = \Omega_1 t$, $\frac{d\Theta_1}{dt} = \Omega_1$, $\frac{d^2\Theta_1}{dt^2} = 0$, consequently $b_2 = \frac{1-K\varphi_\kappa}{W_1\Omega_1}$, while $\frac{db_2(t)}{dt} = 0$, i.e. KSN always provide $\Theta_\kappa = 0$.

In the case

$$\Theta_1(t) = \frac{\varepsilon_1 t^2}{2},\quad \frac{d\Theta_1}{dt} = \varepsilon_1 t,\quad \frac{d^2\Theta_1}{dt^2} = \varepsilon_1,$$

consequently,

$$b_1(t) = \frac{T_1 - T_2 - K\varphi_\kappa}{W_1(\varepsilon_1)t + W_1'(\varepsilon_1)}; \quad \frac{db_2(t)}{dt} = \frac{-W_1(\varepsilon_1)(T_1 - T_2 - K\varphi_\kappa)}{(W_1(\varepsilon_1)t + W_1'(\varepsilon_1))^2};$$
$$\frac{db_2(t)}{dt} = \frac{-(1 - K\varphi_\kappa)W_1(\varepsilon_1)}{W_1(\varepsilon_1)t^2},$$

i.e. KSN provide $\theta_1 \to 0$ with $t \to \infty$.

The sufficiently effective method of the study of SSKR with KSN of KS is L. A. Zade's method, which uses a parametric transfer function of system [1] - [4].

If VV of SSKR with the variable parameters satisfies the proper conditions, then it it is possible to present with the aid of the integral of Fourier

$$\Theta(t) = \frac{1}{2\pi}\int_{-\infty}^{+\infty} \Theta_1(j\omega) e^{j\omega t} d\omega, \qquad (2.6)$$

and the error of SSKR in this case can be determined on the following dependences:

$$\Theta(t) = \int_0^t w_0(t, \zeta)\Theta_1(\zeta)d\zeta, \qquad (2.7)$$

$$\Theta(t) = \frac{1}{2\pi j}\int_{c-j\infty}^{c+j\infty} W_0^*(p, t)\Theta_1(p)e^{pt}dp. \qquad (2.8)$$

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In (2.6)-(2.8) $\Theta_1(j\omega)$ - the composite relative amplitude of the spectrum of function $\Theta_1(t)$; $w(t, \tau)$ the weighing function of error of SSKR; $W_\vartheta(p, t)$ - parametric transfer function of error of SSKR.

If equation (2.1) is represented in the form

$$A(p, t)\Theta(t) = B(p, t)\Theta_1(t), \qquad (2.9)$$

then for case $\Theta_1(t) = \delta(t-\tau)$, $\Theta(t) = w(t, \tau)$ the parametric transfer function of error of SSKR will be expressed [4]

$$W_\vartheta(p, t) = W_\vartheta(p, t)_0 + \sum_{\kappa=1}^{\kappa=n} W_\vartheta(p, t)_\kappa + \dots \qquad (2.10)$$

where $W_\vartheta(p, t)_n$ — n approximation/approach $W_\vartheta(p, t)$:

$$W_\vartheta(p, t)_0 = \frac{B(p, t)}{A(p, t)};$$

$$W_\vartheta(p, t)_{\kappa+1} = -\frac{1}{A(p, t)}\left[\frac{dA(p, t)}{dp}\cdot\frac{dW_\vartheta(p, t)_\kappa}{dt} + \dots + \frac{1}{n!}\frac{d^nA(p, t)}{dp^n}\cdot\frac{d^nW_\vartheta(p, t)_\kappa}{dt^n}\right]. \qquad (2.11)$$

In the slowly changing parameters of SSKR for the preliminary evaluation/estimate of quality of SSKR with KSN it is possible to use the zero approximation W_ϑ(p, t).

For SSKR being investigated with KSN with φ_0=1, φ_0'=1.

$$W_\vartheta(p, t)_0 = \frac{T_1T_2p^4 + (T_1 + T_2 - K\tau_\kappa)p^3 + (1 - K\tau_\kappa)p^2}{T_1T_2p^4 + (T_1 + T_2)p^3 + p^2 + Kp + K\left(W_1\frac{d\Theta_1}{dt} + W_2\frac{d^2\Theta_1}{dt^2}\right)}. \qquad (2.12)$$

With $\Theta_1(t) = \Omega_1 t$, $\frac{d\Theta_1}{dt} = \Omega_1$, $\frac{d^2\Theta_1}{dt^2} = 0$

$$W_3(p, t)_0 = \frac{T_1T_2p^4 + (T_1 - T_2 - K\varphi_\kappa')p^3 + (1 - K\varphi_\kappa)p^2}{T_1T_2p^4 + (T_1 + T_2)p^3 + p^2 + Kp + KW_1'\Omega_1}. \quad (2.12')$$

With $\Theta_1(t) = \frac{\varepsilon_1 t^2}{2}, \frac{d\Theta_1}{dt} = \varepsilon_1 t, \frac{d^2\Theta_1}{dt^2} = \varepsilon_1.$

$$W_4(p, t)_0 = \frac{T_1T_2p^4 + (T_1 - T_2 - K\varphi_\kappa')p^3 + (1 - K\varphi_\kappa)p^2}{T_1T_2p^4 + (T_1 + T_2)p^3 + p^2 + Kp + KW_1'\varepsilon_1 t + KW_1'\varepsilon_1}. \quad (2.12")$$

From analysis (2.12'), (2.12") it follows that during the introduction/input of KSN:

1. $\Theta_\kappa = 0, \Theta_c = \frac{1 - K\varphi_\kappa}{KW_1't + KW_1'}, \Theta_y = 0$ when $\varphi_\kappa = \frac{1}{K}$ and with $t \to \infty$.

2. Stability of SSKR during final adjustment of VV is determined by parameters of SSKR, parameters and sign of VV, which requires switching integral signs of error in function of sign of VV.

3. $\Theta_\kappa = 0, \Theta_y = 0$ in any cases except $\frac{d\Theta_1}{dt} = 0$, if we utilize tuning on first derivative of VV according to the law (Fig. 1c)

$$U_\kappa = W_1\int_0^t\int_0^t \Theta dt. \quad (2.13)$$

For the transient evaluation, using W(p, t)$_0$, it is possible to construct the series of dependences $\Theta(t)$ for fixed values $\Theta(t)$. Each of the dependences $\Theta(t)$ will have only one point, which satisfies

unknown. Connecting the obtained points of smooth curve, let us determine $\theta_\varepsilon(t)$ [4].

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III. Results of the experimental investigation of SSKR with KSN of KS.

Powering unit of servo system is carried out on the following elements/cells: amplidyne EMU-25Az, direct-current motor P12M.

Were investigated SSKR with KSN of KS on first-order derivative and SSKR with two KSN of KS on the first and second derivative of VV. As a result of investigations it is established/installed:

1. With the work of SSKR with one KSN:

a) $\theta_\varepsilon=0$ with any $\varphi(t)$, if the frequency of change $\varphi(t)$ lies/rests at the frequency region, passed by KSN;

b) $\theta_\varepsilon=0$ when $\theta_1(t)=\frac{\varepsilon_1 t^2}{2}$ after certain small time interval t;

c) rms error θ_{ck} when $\theta_1(t)=\theta_{1m}\sin\omega t$ decreases 5-20 times in comparison with SSKR without KSN;

d) free transient processes KSN does not affect;

e) for the stable operation of SSKR with KSN it is necessary during the final adjustment of VV to ensure switching sign $\int \dot{\Theta} dt$ in the function of sign of VV. Dead zone h of BR must be not more (5-7)o/oΩ_1 (Fig. 2a);

f) the selection of factor of amplification I1 must be selected, on the basis of the minimum of transit time t_r during the final adjustment of the velocity discontinuity and minimum Θ_{ck} or $\Theta_{\text{макс}}$ during the final adjustment of VV $\Theta(t) = \Theta_m \sin \omega t$ (Fig. 2b). Fig. 2c presents dependences $t_r = f(T_1)$, $t_r = f(I_1)$, where T_1 - time constant of differentiator, included in the target of the error signal of SSKR.

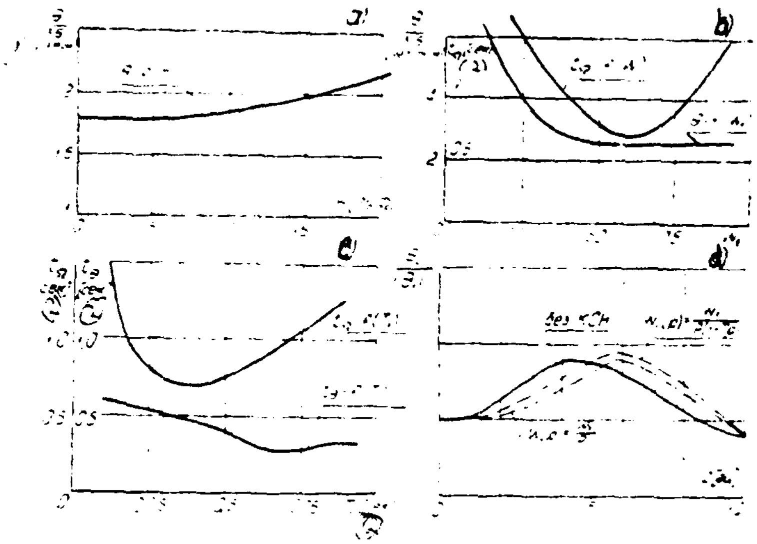

Fig. 2. Graphs/curves of the parameters of SSKR with one KSN.

Key: (1). [ang. min.] (2). s.

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2. With work of SSKR with two KSN.

a) in modes/conditions $\Theta_1(t)=\Omega t$, $\Theta_1(t)=\frac{\varepsilon_1 t^2}{2}$, $\Theta_1(t)=\Theta_{1m}\sin\omega t$, $\Theta_2=0$, $\theta_0=0$;

b) during the introduction/input of KSN requirements on the quality for Dif 2 are weakened/attenuated. The denominator of

transfer function Dif 2 can contain time constants sufficiently high in terms of their values;

c) are optimum values of factors of amplification W_1, W_1' integrators, evaluated in minimum Θ_{κ} or $\Theta_{\text{макс}}$ when $\Theta_1(t) = \Theta_{1m}\sin\omega t$ and minimum of transit time t_3 during the final adjustment of velocity discontinuity Ω_1. Moreover the optimum values W_1, W_1' during the evaluation/estimate according to minimum Θ_{κ} or $\Theta_{\text{макс}}$ different (Fig. 3a, b);

d) error of SSKR during the disturbances/perturbations $\lambda(t)$ on the performing axis it decreases 5-10 times, if Ω_1 in this case is not equal to zero, but the frequency of disturbance/perturbation lies/rests at the frequency region, passed by KSN (Fig. 3c);

e) the value of the time constant T_2 of the real DIF2 for the quality of work of SSKR with KSN practically does not affect (Fig. 3d).

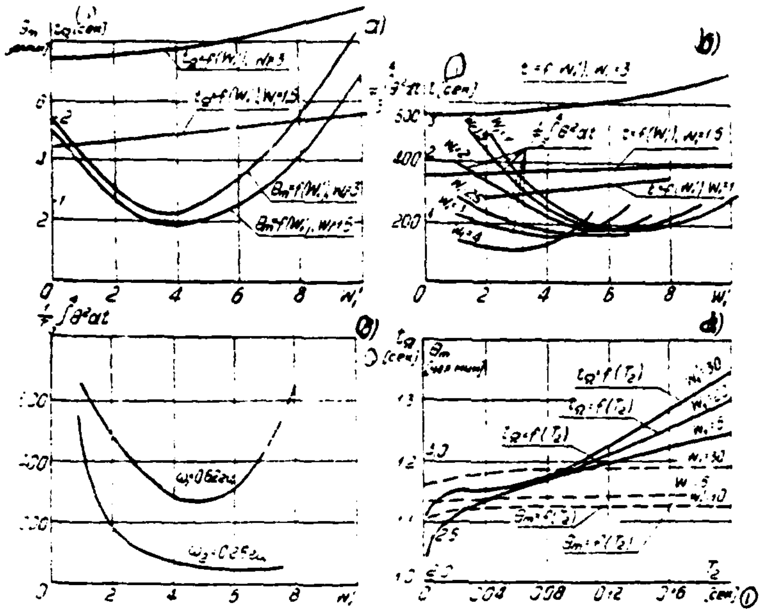

Fig. 3. Graphs/curves of the parameters of SSKR with two KSN.

Key: (1). s.

Conclusion/output.

1. Introduction/input of KSN of KS is effective means of increase in accuracy of SSKR.

2. KSN of KS can be used in new developments and in modernized SSKR, since their use/application does not require treatment/processing main circuit of SSKR, but is provided for only

introduction/input of series/row of supplementary simple devices/equipment.

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